Stringent limits on the $\pi^0 \to \gamma X,\ X \to e^+e^-$ decay from neutrino experiments and constraints on new light gauge bosons

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We report new limits on the $\pi^0 \to \gamma X$ decay of the neutral pion into a photon and a new gauge boson X followed by the decay $X \to e^+e^-$. If this process exist, one would expect a flux of high energy X's produced from π^0's generated by the proton beam in a neutrino target. The X's would then penetrate the downstream shielding and be observed in a neutrino detector via their decays. Using bounds from the NOMAD and PS191 neutrino experiments at CERN that searched for an excess of e^+e^- pairs from heavy neutrino decays, stringent limits on the branching ratio as small as $Br(\pi^0 \to \gamma X) \lesssim 10^{-15}$ are obtained. These limits are several orders of magnitude smaller than the previous experimental and cosmological bounds. The obtained results are used to constrain models, where the X interacts with quarks and leptons, or it is a new vector boson mixing with photons, that transmits interaction between our world and hidden sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields.

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Many extensions of the Standard Model (SM) such as GUTs [1], super-symmetric [2], super-string models [3] and models including a new long-range interaction, i.e. the fifth force [4], predict an extra $U^{'}(1)$ factor and therefore the existence of a new gauge boson X corresponding to this new group. The predictions for the mass of the X boson are not very firm and it could be light enough ($M_X \ll M_Z$) for searches at low energies. If the mass M_X is of the order of the pion mass, an effective search could be conducted for this new vector boson in the radiative decays of neutral pseudoscalar mesons $P \to \gamma X$, where $P = \pi^0, \eta$, or η', because the decay rate of $P \to \gamma +$ *any new particles with spin 0 or* $\frac{1}{2}$ proves to be negligibly small [5]. Therefore, a positive result in the direct search for these decay modes could be interpreted unambiguously as the discovery of a new light spin 1 particle, in contrast with other experiments searching for light weakly interacting particles in rare K, π or μ decays [5–7].

The decay $\pi^0 \to \gamma X$ can also occur in several interesting extensions of the SM that suggest the existence of, so-called, "hidden" sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields. These are sectors of weakly interacting massive particles (WIMPs), that do not interact with the ordinary matter directly and couple to it by gravity and possibly by other very weak forces. If the mass scale of a hidden sector is too high, it will be experimentally unobservable. However, there is a class of models where Dark Matter WIMPs have interactions with the SM mediated by $U_h(1)$ gauge group and the corresponding hidden gauge boson could be light, see e.g. [8–10]. The fact that the X coupling strength may be in the experimentally accessible and theoretically interesting regions, makes further searches for X's very attractive at the high intensity frontier [11].

From the analysis of data from earlier experiments, constraints on the branching ratio for the decay of $P \to \gamma + X$ range from 10^{-7} to 10^{-3} depending on whether X interacts with both quarks and leptons or only with quarks [12]. Direct searches for a signal from $\pi^0 \to \gamma X$ decay have been performed in a few experiments with two different methods: i) searching for a peak in inclusive photon spectra from two-body $\pi^0 \to \gamma + nothing$ decays, where "nothing" means that X is not detected because it either has a long life time or decays into $\nu\overline{\nu}$ pairs [13–17], and ii) searching for a peak in the invariant mass spectrum of e^+e^- pairs from π^0 decays, which corresponds to the decay $X \to e^+e^-$ [16, 17].

The best experimental limit on the branchning ratio of the decay $\pi^0 \to \gamma X$, $Br(\pi^0 \to \gamma X) < (3.3 - 1.9) \times 10^{-5}$ ($90\% C.L.$) for X masses ranging from 0 to 120 MeV, was obtained by the NOMAD experiment at CERN [18]. Using 450 GeV proton collisions with the SPS neutrino target as a source of high energy X's from $\pi^0 \to \gamma X$ decays, they searched for a signal from the Primakoff conversion $X \to \pi^0$ in their detector [19]. The best bound for the branching ratio $Br(\pi^0 \to \gamma X)Br(X \to e^+e^-) < 2 \times 10^{-4} - 4 \times 10^{-6}$ for the X mass range $25 < M_X < 120\ MeV$ was obtained by the SINDRUM collaboration at PSI [16]. In this letter we show that more stringent limits on the decay $\pi^0 \to \gamma X$, followed by the decay $X \to e^+e^-$ can be obtained from the results of sensitive searches for an excess of single isolated e^+e^- pairs from decays of heavy neutrinos in the sub-GeV mass range by the PS191 [20, 21] and NOMAD [22–24] experiments at CERN.

Consider first the NOMAD experiment on search for the decay $\nu_h \to \nu e^+e^-$ of a heavy neutrino ν_h into a lighter neutrino and e^+e^- pair performed at the CERN West Area Neutrino Facility (WANF) [22]. The WANF provides an essentially pure ν_μ beam for neutrino experiments. It consists of a Be target irradiated by 450 GeV protons from the CERN SPS. The secondary hadrons are focused by the horn and the reflector, and protons that have not interacted in the target, secondary hadrons and muons that do not decay are absorbed by a 400 m thick

shielding made of iron and earth. The NOMAD detector described in Ref. [25] is located at 835 m from the neutrino target. It consists of a number of sub-detectors most of which are located inside a 0.4 T dipole magnet with a volume of $3.5 \times 3.5 \times 7.5$ m^3 including an active target of drift chambers (DC) with a mass of 2.7 tons.

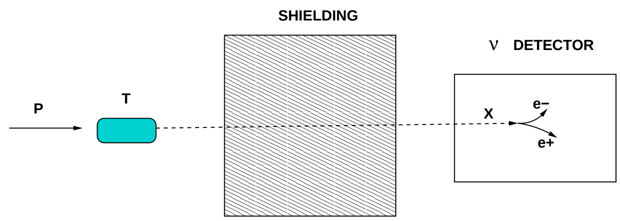

FIG. 1: Schematic illustration of a proton beam dump experiment on search for $\pi^0 \to \gamma X \to e^+e^-$ decay chain: neutral pions generated by the proton beam in the neutrino target (T) produce a flux of high energy X's which penetrate the downstream shielding and decay into e^+e^- pair in a neutrino detector.

If the decay $\pi^0 \to \gamma X$ exists, one expects a flux of high energy X bosons from the WANF target, since π^0's are abundantly produced in the forward direction by high energy protons either in the target or in the beam dump following the decay tunnel. If X is a relatively long-lived particle, this flux would penetrate the downstream shielding without significant attenuation and would be observed in the NOMAD detector via the $X \to e^+e^-$ decay into a high energy e^+e^- pair, as schematically illustrated in Fig. 1. The occurrence of $X \to e^+e^-$ decays would appear as an excess of isolated e^+e^- pairs in NOMAD above those expected from standard neutrino interactions. The experimental signature of these events is clean and they can be selected with small background due to the excellent NOMAD capability for precise measurements of e^+e^- pairs, see example [24, 26]. As the final states of the decays $\nu_h \to \nu e^+e^-$ and $X \to e^+e^-$ are identical, the results of the searches for the former can be used to constrain the later for the same e^+e^- invariant mass regions.

The calculated flux and energy spectrum of π^0 produced in the Be target were used to predict the flux of X's with momenta pointing to the NOMAD fiducial area as a function of the X mass, see Fig. 2. The search for the $\nu_h \to \nu e^+e^-$ decay described in [22] corresponds to the total number of 4.1×10^{19} protons on target (pot). The strategy of the analysis was to identify $\nu_h \to \nu e^+e^-$ candidates by reconstructing in the DC isolated low invariant mass e^+e^- pairs that are accompanied by no other activity in the detector. The measured rate of e^+e^- pairs was then compared to that expected from known sources. By selecting only two tracks identified as an e^+e^- pair with energy > 4 GeV and invariant mass $M_{e^+e^-} < 95$ MeV, the inverse total momentum pointing back to the target, and forming a vertex within the DC fiducial volume, an excess of 2.1 events compatible with background expectations was observed. For a given flux

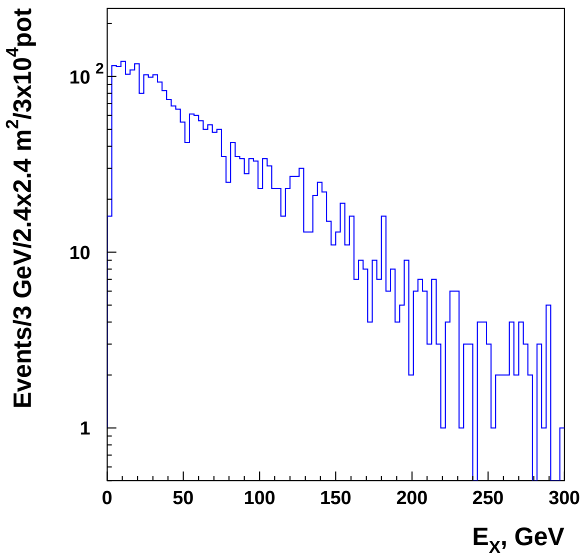

FIG. 2: Combined energy spectrum of X bosons with mass M_X=10 MeV from the SPS neutrino target and from the beam dump region at the NOMAD detector calculated for $Br(\pi^0 \to \gamma X) = 1$.

$d\Phi(M_X, E_X, N_{pot})/dE_X$ of X's the expected number of $X \to e^+e^-$ decays occuring within the fiducial length L of the NOMAD detector located at a distance L' from the neutrino target is given by

$$N_{X\to e^+e^-} = Br(\pi^0 \to \gamma X)Br(X \to e^+e^-)\int \frac{d\Phi}{dE_X} \cdot exp\Big(-\frac{L'M_X}{P_X\tau_X}\Big)\Big[1 - exp\Big(-\frac{LM_X}{P_X\tau_X}\Big)\Big]\varepsilon A dE_X \quad (1)$$

where E_X, P_X, and τ_X are the X energy, momentum and the lifetime at rest, respectively, ε is the e^+e^- pair reconstruction efficiency, N_{pot} is the number of pot. The acceptance A of the detector was calculated tracing X's produced in the Be-target or beam dump to the detector taking the relevant momentum and angular distributions into account. As an example for a mass $M_X = 10$ MeV, $A = 8.5\%$ and $\varepsilon \simeq 20\%$. The X flux calculated as a function of the X energy is shown in Fig. 2.

The final 90% $C.L.$ exclusion region in the $Br(\pi^0 \to \gamma X)Br(X \to e^+e^-)$ vs τ_X plane shown in Fig. 3 together with the PS191 result (see below) is calculated by using the relation $N^{90\%}_{e^+e^-} > N_{X\to e^+e^-}$, where $N^{90\%}_{e^+e^-}$ (= 2.1 events) is the 90% $C.L.$ upper limit for the expected number of signal events [22]. Our result is sensitive to a branching ratio $Br(\pi^0 \to \gamma X) \gtrsim 10^{-15}$, which is more than nine orders of magnitude smaller than the previous limit from the experiment[16]. Over most of the τ_X region, the X lifetime is sufficiently long, that $LM_X/p_X\tau_X \ll L'M_X/p_X\tau_X \ll 1$.

To obtain limits for the region $M_X > 95$ MeV, we consider next the results of the PS191 neutrino experiments

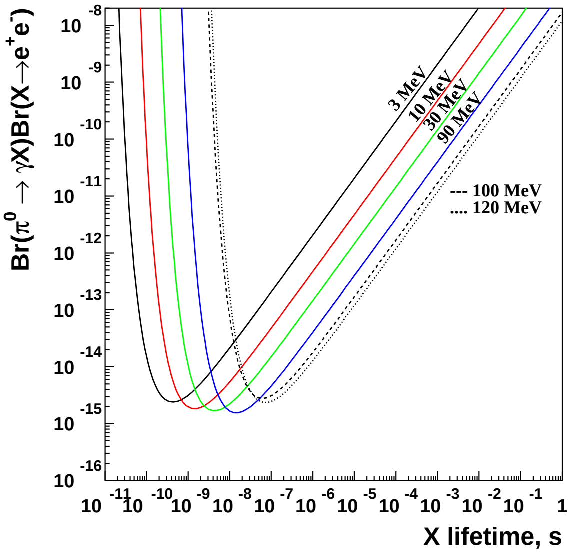

FIG. 3: The 90% *C.L.* upper limits on the branching ratio $Br(\pi^0 \to \gamma X)Br(X \to e^+e^-)$ versus τ_X from the NOMAD (solid) and PS191 (dashed, dotted) experiments. The numbers near the curves indicate the corresponding values of M_X.

at CERN that searched for decays $\nu_h \to \nu e^+e^-$ of heavy neutrinos produced in 2-body decays $\pi, K \to e, \mu + \nu_h$ in the ν_h mass range from $\simeq 10$ to $\simeq 350$ MeV [20, 21]. This experiment, specifically designed to search for neutrino decays in a low-energy neutrino beam, was performed by using 19.2 GeV protons from the CERN Proton Synchrotron with the total number of 0.86×10^{19} pot. The PS191 detector, located at the distance of 128 m from the target, consist of a 12 m long decay volume, eight chambers located inside the volume to detect charged tracks and followed by a calorimeter. The events searched for in the experiment were requested to consist of two tracks originating from a common vertex in the decay volume and giving rise to at least one shower in the calorimeter. No single e^+e^- events were observed and limits were established on the $\nu_{e,\mu} - \nu_h$ mixing strength as a function of the ν_h mass.

Using Eq.(1) for the PS191 case, similar to above considerations, we calculte the 90 % *C.L.* branching ratio limit curve shown in Fig. 3 together with the result from NOMAD. For the mass region $95 < M_X < 135$ MeV/c^2 the best limits from PS191 are in the region $Br(\pi^0 \to \gamma X)Br(X \to e^+e^-) \lesssim (2-4) \times 10^{-15}$. In this estimate the average X momentum is $< p_X > \simeq 1$ GeV and the decay region length is $l = 7$ m. The results obtained were also cross checked with the limits set by PS191 on the $\nu_{e,\mu} - \nu_h$ mixing strength [20] and found to be in agreement. For the mass region below 95 MeV, NOMAD provides better bounds than PS191. The $\pi^0 \to \gamma X$ decay rate constrained by NOMAD is small enough to produce a detectable excess of e^+e^- events in the PS191 experiment. In addition, for masses $M_X \lesssim 10$ MeV the reconstruction efficiency drops, because the opening angle of the e^+e^- pair is $\simeq M_X/E_X \lesssim 10^{-2}$ rad, which is small enough to be resolved in the PS191 detector. Hence, some events would be misidentified as a single track and, would be rejected.

The obtained results can be used to impose constraints on the magnitude of the coupling constant $\alpha_X = g_X^2/4\pi$ for the interaction of X bosons with both quarks and leptons, which can be written in the form:

$$L_X = g_X(Q_{BX}B^i + Q_{eX}L_e^i + Q_{\mu X}L_\mu^i + Q_{\tau X}L_\tau^i)X^i \quad (2)$$

where $B^i = \sum_{q=u,d,s,..} \overline{q}\gamma^i q$, $L_e^i = \overline{e}\gamma^i e + \overline{\nu}_{eL}\gamma^i \nu_{eL}$, ..., see e.g. [5, 7]. Assuming charges $Q_{BX} \simeq Q_{eX} \simeq 1$, we found

$$\alpha_X < 3.4 \times 10^{-13} \frac{1}{M_X[MeV]} \Big(1 - \frac{M_X^2}{M_\pi^2}\Big)^{-3/2}, \quad (3)$$

which is valid for $M_X < M_\pi$, where M_π is the mass of π^0, and $\tau_X \gtrsim 10^{-10} M_X$[MeV] s. This limit is more restrictive than those obtained in [6, 7], and than bounds reported by NOMAD [18]. Less stringent limits (by a factor $\simeq \alpha$) could be obtained for the cases where the X interacts only with leptons, or when it is a leptophobic boson which interacts only with quarks and decays dominantly into e^+e^- pair through the quark loop if its mass $M_X > 2m_e$ [6, 7].

We can also constrain recent models, where new vector-like bosons mediate interaction between our world and hidden sectors due to the kinetic mixing term

$$L_{int} = -\frac{1}{2}\chi F_{\mu\nu}V^{\mu\nu}. \quad (4)$$

where, χ is the mixing strength, and $F^{\mu\nu}$, $V^{\mu\nu}$ are the ordinary photon and hidden vector field strengths, respectively, see e.g. [10]. As follows from (4), any source of γ's could produce kinematically possible massive states V according to the appropriate mixings. If the mass of V is below the mass of π^0, it can be produced in the decay $\pi^0 \to \gamma X$, with the subsequent decay of X into e^+e^- pair [27]. The corresponding branching ratio is given by:

$$Br(\pi^0 \to \gamma V) = 2\chi^2\Big(1 - \frac{M_V^2}{M_\pi^2}\Big)^3 \quad (5)$$

For V masses below the π^0-meson mass, $M_V \lesssim M_\pi$, the dominant V boson decay is e^+e^- with a rate which, for small mixing, is given by:

$$\Gamma(V \to e^+e^-) = \frac{\alpha}{3}\chi^2 M_V \sqrt{1 - \frac{4m_e^2}{M_V^2}}\Big(1 + \frac{2m_e^2}{M_V^2}\Big) \quad (6)$$

Using Eqs.(5,6) we can determine the 90% *C.L.* exclusion regions in the $(M_V; \chi)$ plane from the results of the NOMAD [22] and PS191 [20] experiments, which are shown in Fig. 4 together with the area excluded by the electron beam dump experiment E137 at SLAC [28], see Ref.[29]

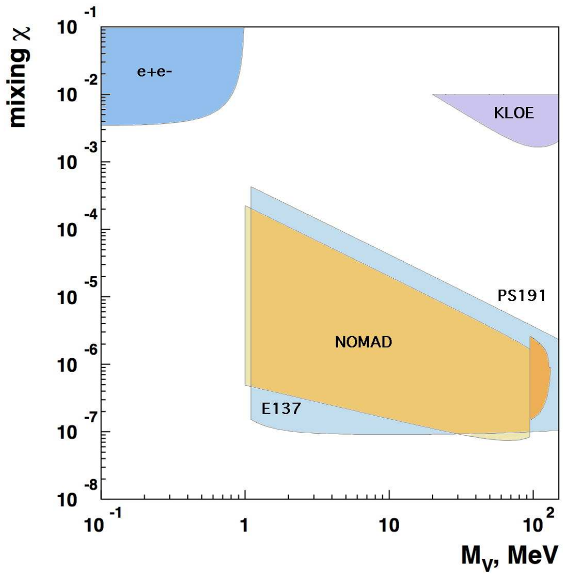

FIG. 4: 90% *C.L.* exclusion regions in the $(M_V;\chi)$ plane obtained from the results of the NOMAD [22], PS191 [20], and positronium [30] experiments. The areas excluded by the electron beam dump experiment E137 [28] and by the KLOE experiment [31] are also shown for comparison.

and discussion therein, positronium experiment searching for the decay $e^+e^- \to \gamma V$ [30] and recent results from KLOE [31]. The shape of the exclusion contour from the PS191 experiment corresponding to the X mass range $M_V > 95$ MeV is defined mainly by the phase space factor in (5). One can see, that the NOMAD exclusion region falls basically within that of the E137 experiment. However, the fact that the NOMAD events are generated by the proton beam, while the E137 events are originated from the electron beam dump is important if, e.g. the X is a leptophobic boson which interacts dominantly with quarks. The attenuation of the X- flux due to X interactions with matter was found to be negligible, e.g. for couplings of (3) the X boson mean free path in iron is $\gg$ 100 km, as compared with the iron and earth shielding total length of 0.4 km used for the NOMAD beam.

In summary, using sensitive limits from the PS191 and NOMAD experiments on heavy neutrino decays $\nu_h \to \nu e^+e^-$ in the sub-GeV mass range, new stringent limits on the branching fraction $Br(\pi^0 \to \gamma X) \lesssim 10^{-8} - 10^{-15}$, for X masses $1 < M_X < 135$ MeV and lifetime $10^{-11} < \tau_X < 1$ s, are obtained. Our best result is sensitive to a branching ratio $Br(\pi^0 \to \gamma X) \gtrsim 10^{-15}$, which is about nine orders of magnitude smaller than the previous limit from the SINDRUM experiment[16]. It is also a factor $\simeq 100$ more stringent than the bound from cosmological considerations [32]. The obtained results are used to set new limit on the X coupling strength to lepton and quarks, and also to constrain models, in which mixing between photons and a new vector-like bosons mediates interaction between our world and hidden sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields. For the X mass range $\lesssim M_\pi$ the obtained limits on the mixing χ are more stronger than those recently derived by the experiment KLOE [31], and comparable with those obtained in Ref.[29, 34]. Stringent constraints on mixing strength η obtained from SM1987A observations, have been recently reported in [33]. We demonstrate a significant potential of experiments similar to NOMAD for the future more sensitive searches for new physics at the high intensity frontier [11]. For example, stringent limits for the extended sub-GeV X boson mass range $M_X > M_\pi$ could be obtained from the searches for η, η' mesons decays $\eta, \eta' \to \gamma X$ with the subsequent decays $X \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \mu^\pm e^\mp, \mu^\pm\pi^\mp, ...$ We note that limits on the decays $\eta, \eta' \to \gamma X$ could also be obtained from PS191 or other existing data provided cross-sections for η, η' productions in the forward direction in $p - Be$ collisions are known. These limits are expected to be more restrictive than those recently reported by the A1 collaboration from the search for the decay $X \to e^+e^-$ in a fixed target experiment [35].

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